Lesson 10

Design Evaluation of Particulate Wet Scrubbing Systems

Goal

To familiarize you with the factors to be considered when evaluating particulate-pollutant scrubber design plans.

Objectives

At the end of this lesson, you will be able to do the following:

1. Explain the importance of the following factors in scrubber design:
    - Dust properties
    - Exhaust gas characteristics
    - Static pressure drop
    - Liquid flow rate
    - Collection efficiency
    - Removal of entrained droplets
2. Estimate the collection efficiency and pressure drop of a venturi scrubber using appropriate equations and graphs
3. Use the contact power method to estimate collection efficiency
4. Describe the strengths and limitations of the contact power method.

Introduction

In performing an evaluation of a new scrubbing system design, especially from a regulatory perspective, the major issue is whether the proposed design will achieve the required particle and/or gas removal efficiencies. In addition to addressing this basic issue, there is also the question of how effectively the proposed system will operate. For example, will the system be able to handle a sufficient range of expected operating conditions without requiring excessive maintenance or downtime? Answering these questions is difficult since there is no one set of theoretical equations that will provide an absolute answer.

There are three basic approaches to evaluating the capability of a scrubbing system: (1) empirical relationships based on historical test data on similar scrubbers, (2) theoretical models based on basic engineering principles and (3) pilot scale test data. A scrubber vendor has access to all three (especially historical information) when designing a system. A person reviewing the design generally does not have easy access to this type of information. When conducting a review, first, start with the theoretical equations to verify the basic design then supplement this information with data on similar systems obtained from literature or the scrubber vendor.

In the previous lessons, you have become familiar with operating and maintenance data on a variety of scrubbing systems. This lesson will first present an overview of the general parameters that affect scrubber design and then cover the following:

- Theoretical models for estimating particle collection efficiency
- Estimating venturi static pressure drop

A reviewer can then use the equations in this lesson coupled with historical data to evaluate scrubbing systems. You will have the opportunity to practice using the equations presented in this lesson by working the three problems in the Review Exercise.

Particulate Scrubber Design Factors

In order to properly design a particulate wet scrubber, the vendor must obtain as much information as possible concerning the characteristics of the flue gas stream to be treated. This information must be obtained or estimated for both the average and maximum ranges that will occur. Scrubbing systems must be able to operate effectively at both the normal day-to-day conditions as well as to accommodate any maximum ranges.

Basically, the two most important site-specific parameters that must be evaluated by the designer are the particle and gas stream characteristics:

- **Dust Properties** - These include particle size distribution, concentration and chemical composition. The particle size distribution is the most important factor that affects scrubber design and operation. However, particle size distribution data is rarely available for most sources and generally must be estimated from similar type sources. The average and maximum particle concentrations (or grain loading) must be obtained to properly size the scrubber and the solids removal system. Chemical composition of the dust particle is important to determine if the material will cause any plugging problems or precipitate problems.

- **Exhaust Gas Characteristics** - These include the average and the maximum flow rates, moisture content, and chemical composition The flow rates determine the volume of gas to be treated and therefore, the size of the scrubbing system. The moisture content and chemical composition are important in determining the potential corrosiveness of any liquid streams, pH levels, saturation conditions and spent liquid treatment and disposal requirements.

Vendors utilize the above information as the basis for their proposed design and provide estimates or guarantees for the following important scrubber operating parameters.

- **Static Pressure Drop** - This is dependent on the desired removal efficiency and mechanical design of the scrubber system. Table 10-1 presents typical ranges for various wet scrubbers.
- **Liquid Flow Rate** - This parameter is based on the evaporation rate and type of scrubbing system utilized. Values need to be identified for both normal and maximum operating conditions. Also, if applicable, the recirculation rate and permissible levels of suspended solids in the recirculated liquid need to be identified. Table 10-1 lists typical ranges for various wet scrubbers.
- **Collection Efficiency** - The particle removal rate at both normal and maximum levels should be identified.
- **Removal of Entrained Droplets** - The type and efficiency of the mist removal system should be clearly stated.

Table 10-1. Ranges of pressure drops and liquid-to-gas (L/G) ratios for various wet scrubbers

Scrubber	Pressure drop, Δp		Liquid-to-gas ratio[1]	
	kPa	in. H_2O	L/m^3	gal/1000 ft^3
Venturi	1.5-25.0	5.0-100.0	0.4-5.0	3.0-40.0
Spray tower	0.12-0.75	0.5-3.0	0.7-2.7	5.0-20.0
Cyclonic spray	0.4-4.0	1.5-10.0	0.3-1.3	2.0-10.0
Moving bed (good for removing particulate and gaseous pollutants)	0.5-6.0	2.0-24.0	0.4-8.0	3.0-60.0
Orifice (self-induced spray)	0.5-4.0	2.0-10.0	0.07-0.7	0.5-5.0
Mechanically aided (fan)	1.0-2.0	4.0-8.0	0.07-0.5	0.5-4.0

1. Higher L/G reflects those used for gas absorption.

All scrubbers are capable of removing particles from a gas stream. Because of their ability to achieve high particle removal efficiencies and handle heavy grain loadings without plugging, venturi scrubbers are the most popular scrubber used to remove particulate matter. Venturis produce high particle to liquid droplet velocities in order to achieve good particle removal and therefore are limited in their ability to remove gases. The remainder of this lesson will provide an overview of theoretical equations (mainly venturi type systems) to predict scrubber efficiency along with examples of their use.

Estimating Collection Efficiency and Pressure Drop

A number of theories have been developed from basic particle-movement principles to explain the action of wet scrubbing systems. Many of these start from firm scientific concepts, but yield only qualitative results when predicting collection efficiencies or pressure drops. The interaction of particulate matter having a given particle-size distribution with water droplets having another size distribution is not easy to express in quantitative terms. As a result of this complexity, experimentally determined parameters are usually needed to approach reality.

Collection Efficiency

Collection efficiency is frequently expressed in terms of penetration. **Penetration** is defined as the fraction of particles (in the exhaust stream) that passes through the scrubber uncollected. Penetration is the opposite of the fraction of particles collected (i.e. collection efficiency), and is expressed as:

$$\mathrm{Pt} = 1 - \eta \qquad (10\text{–}1)$$

Where: Pt = penetration
η = collection efficiency

Wet scrubbers usually have an efficiency curve that fits the relationship of

$$\eta = 1 - e^{-f(\text{system})} \qquad (10\text{-}2)$$

Where: η = collection efficiency
e = exponential function
f (system) = some function of the scrubbing system variables

By substituting for efficiency, penetration can be expressed as:

$$\begin{aligned} \mathrm{Pt} &= 1 - \eta \qquad (10\text{-}3) \\ &= 1 - \left(1 - e^{-f(\text{system})}\right) \\ &= e^{-f(\text{system})} \end{aligned}$$

An equation for the scrubbing system variables, f (system), can be developed for a particular scrubber design. A vendor can measure the operating variables and the collection efficiency of an existing or pilot scale unit. This information can then be used to evaluate the efficiency of the system. Scrubber vendors and various consultants have developed equations and assembled data that can be used to design and evaluate their specific scrubbers. Unfortunately, much of this information is proprietary. In addition, an equation that has been designed for a venturi scrubber may not work well for evaluating the design of an orifice or cyclonic scrubber. In other words, there is not one specific equation that can be used to estimate the collection efficiency of every scrubbing system. A summary of equations used for predicting collection efficiency can be found in the *Wet Scrubber System Study*, Volume 1, *Scrubber Handbook* (Calvert et al. 1972). Theoretical penetration models estimate the penetration value as a function of particle size. This correlation can be applied to the particle size distribution of a proposed system to estimate overall collection efficiency.

Limitations in using these correlations include the following: (1) there are often very complex mathematical relationships involved, and (2) all the data inputs are either not readily available or non-existent and must be estimated. Below is an example of one of the more refined models for the venturi scrubber.

The Infinite Throat Model for Estimating Venturi Scrubber Efficiency

One method for predicting particle collection efficiency in a venturi scrubber is the **infinite-throat model** (Yung et al. 1977). This model is a refined version of the Calvert correlation given in the *Wet Scrubber System Study* (Calvert et al. 1972). The equations presented in the infinite-throat model assume that all particles are captured by the water in the throat section of the venturi. Two studies found that this method correlated very well with actual venturi scrubber operating data (Yung et al. 1977 and Calvert et al. 1978).

A summary of the infinite throat model using metric units is presented in equations 10-4 through 10-12. Equation 10-4 is the actual equation which predicts the penetration (Pt) for **one** particle size (diameter). Equations 10-5 through 10-12 provide calculations for parameters that are used for determining particle penetration. As discussed later, to obtain an *overall* penetration ($\overline{\text{Pt}}$), you must integrate over the entire particle-size distribution.

$$\ln \text{Pt}\left(d_p\right) = -B\,\frac{4K_{po} + 4.2 - 5.02K_{po}^{0.5}\left(1 + \dfrac{0.7}{K_{po}}\right)\tan^{-1}\sqrt{\dfrac{K_{po}}{0.7}}}{K_{po} + 0.7} \qquad (10\text{-}4)$$

Where:

	$Pt(d_p)$	=	penetration for one particle size
	B	=	parameter characterizing the liquid-to-gas ratio, dimensionless
	K_{po}	=	inertial parameter at throat entrance, dimensionless

Note: Equation 10-4 was developed assuming that the venturi has an infinite-sized throat length. This is valid only when ℓ in the following equation is greater than 2.0.

$$\ell = \frac{3\ell_t C_D \rho_g}{2 d_d \rho_l}$$

Where:

ℓ = throat length parameter, dimensionless
ℓ_t = venturi throat length, cm
C_D = drag coefficient for the liquid at the throat entrance, dimensionless
ρ_g = gas density, g/cm^3
d_d = droplet diameter, cm
ρ_l = liquid density, g/cm^3

As you can see from Equation 10-4, two parameters, K_{po} and B, must be found before calculating the particle penetration. K_{po}, the inertial parameter at the throat entrance, is calculated in Equation 10-5.

$$K_{po} = \frac{d_p^{\,2} v_{gt}}{9 \mu_g d_d} \tag{10-5}$$

Where:

K_{po} = inertial parameter at the throat entrance, dimensionless
d_p = particle aerodynamic resistance diameter, cmA*
v_{gt} = gas velocity in the throat, cm/s
μ_g = gas viscosity, g/cm•s
d_d = droplet diameter, cm

* The “A” signifies that the diameter is an aerodynamic diameter instead of a physical diameter.

All the variables in Equations 10-5 can be measured empirically except for the droplet diameter (d_d) which is calculated in the following equation known as the Nukiyama Tanasawa equation.

$$d_d = \frac{50}{v_{gt}} + 91.8(L/G)^{1.5} \tag{10-6}$$

Where:

d_d = droplet diameter, cm
v_{gt} = gas velocity in the throat, cm/s
L/G = liquid-to-gas ratio, dimensionless

Once the droplet diameter is calculated using empirically derived values for the gas velocity (at the throat) and the L/G ratio, the value for K_{po} can be determined (in Equation 10-5).

The second variable in Equation 10-4, the parameter characterizing the liquid-to-gas ratio (B), can be calculated using Equation 10-7.

$$B = (L/G)\frac{\rho_l}{\rho_g C_D} \tag{10-7}$$

Where:
- B = parameter characterizing liquid-to-gas ratio, dimensionless
- L/G = liquid-to-gas ratio, dimensionless
- ρ_l = liquid density, kg/m3
- ρ_g = gas density, kg/m3
- C_D = drag coefficient for the liquid at the throat entrance, dimensionless

Values for L/G, liquid density, and gas density can be measured. The value for C_D is calculated using Equation 10-8.

$$C_D = 0.22 + \frac{24}{N_{Re\,o}}\left(1 + 0.15\,N_{Re\,o}^{0.6}\right) \tag{10-8}$$

Where:
- C_D = drag coefficient for the liquid at the throat entrance, dimensionless
- N_{Reo} = Reynolds Number for the liquid droplet at the throat inlet, dimensionless

The Reynolds Number is determined in Equation 10-9.

$$N_{Re\,o} = \frac{v_{gt} d_d}{\nu_g} \tag{10-9}$$

Where:
- N_{Reo} = Reynolds Number for the liquid at the throat entrance, dimensionless
- v_{gt} = gas velocity in the throat, cm/s
- d_d = droplet diameter, cm
- ν_g = gas kinematic viscosity, cm^2/s

Equation 10-9 requires a value for the droplet diameter (d_d) which was determined earlier (see Equation 10-6). The gas kinematic viscosity (ν_g) is a variable that can be measured. Once, you have solved for the parameters K_{po} and B, you can calculate the particle penetration by using Equation 10-4.

Other equations that are included with the infinite throat model are presented below. Depending on data availability, K_{pg}, the inertial parameter for mass-median diameter is used instead of K_{po}. A method for using the parameters K_{pg} and B to estimate particle penetration will be shown later.

$$K_{pg} = \frac{d_{pg}^{\,2} v_{gt}}{9\mu_g d_d} \tag{10-10}$$

Where: K_{pg} = inertial parameter for mass-median diameter, dimensionless
d_{pg} = particle aerodynamic geometric mean diameter, cmA
v_{gt} = gas velocity in the throat, cm/s
μ_g = gas viscosity, g/cm•s
d_d = droplet diameter, cm

Equation 10-10 is identical to Equation 10-5 which calculates K_{po} except for the particle aerodynamic diameter used. Equation 10-5 uses the particle aerodynamic resistance diameter (d_p) and Equation 10-10 uses the particle aerodynamic geometric mean diameter (d_{pg}). The parameter, d_{pg}, is calculated in Equation 10-11.

$$d_{pg} = d_{ps}\left(C_c \times \rho_p\right)^{0.5} \tag{10-11}$$

Where: d_{pg} = particle aerodynamic geometric mean diameter,µmA
d_{ps} = particle physical, or Stokes, diameter, µm
C_c = Cunningham slip correction factor,dimensionless
ρ_p = particle density, g/cm^3

The Cunningham slip correction factor, C_c, which is required for Equation 10-11 can be found by solving Equation 10-12.

$$C_c = 1 + \frac{\left(6.21 \times 10^{-4}\right)T}{d_{pg}} \tag{10-12}$$

Where: C_c = Cunningham slip correction factor, dimensionless
T = absolute temperature, K
d_{ps} = particle physical, or Stokes, diameter, µm

With values for C_c and d_{pg}, you can solve Equation 10-10 for K_{pg}, the inertial parameter for mass-median diameter.

The infinite throat model becomes more useful for air pollution applications when the *overall* penetration ($\overline{Pt}$) for a particle-size distribution is calculated. To obtain an overall penetration ($\overline{Pt}$), you must integrate over the entire particle-size distribution.

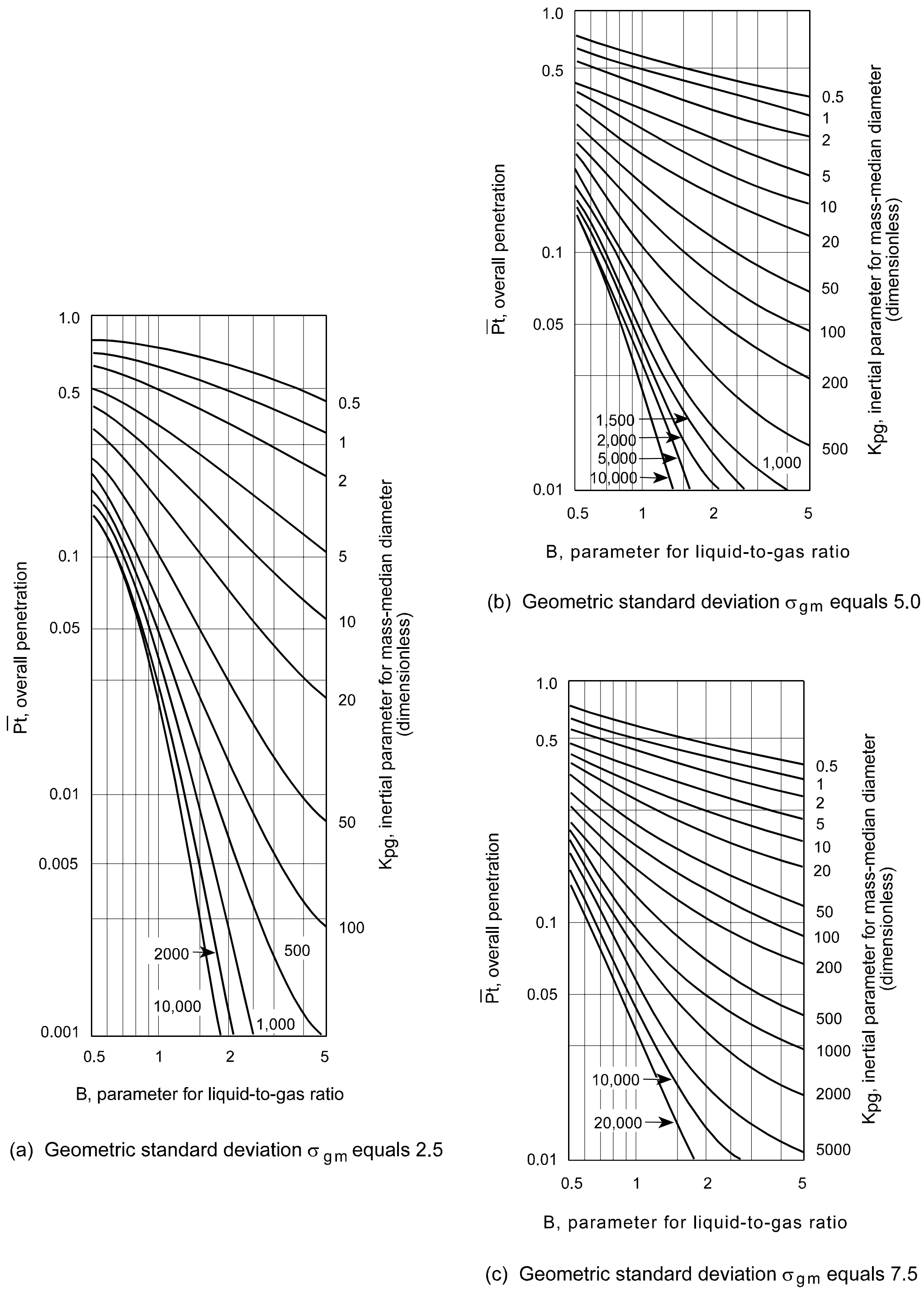
As an aid in calculating the overall penetration, Equations 10-4 (penetration for one particle size) through 10-12 were solved for the overall penetration assuming a log-normal particle-size distribution at various values of K_{pg} and B. These results are plotted in Figures 10-1(a), (b), and (c) (Yung et al. 1977).

In Figure 10-1, $\overline{Pt}$, the overall penetration, is plotted versus B, a dimensionless parameter characterizing the liquid-to-gas ratio, and versus K_{pg}, a dimensionless inertial parameter for mass-median diameter. Each figure has been plotted for a different geometric standard deviation for particle size, i.e., 2.5, 5.0, and 7.5. Figure 10-1(a) (with a geometric standard deviation of 2.5) represents particles with a narrower size range than Figures 10-1(b) and 10-1(c) (with geometric standard deviations of 5.0 and 7.5 respectively).

These figures show that collection increases (penetration decreases) as the values for both B and K_{pg} increase. From Equations 10-7 and 10-10, the value of B increases as the liquid-to-gas ratio increases and the value of K_{pg} increases as the particle geometric mean diameter increases, assuming other parameters in the equations remain constant.

Focusing on Figure 10-1(a), let's compare the particle collection of two applications: one with a K_{pg} = 0.5 and another with a K_{pg} = 50. As you can see, where the value for K_{pg} is 0.5 (top line), particle collection starts off low and improves slightly as the value for B increases. This supports what we already know, namely, that small particles (K_{pg} is 0.5) are difficult to capture and increasing the liquid-to-gas ratio only slightly enhances collection. Whereas for larger particles, (K_{pg} is 50), particle collection starts at a higher level and improves dramatically as the liquid-to-gas ratio increases.

In summary, by knowing the particle-size distribution of the dust from an industrial source and the operating conditions of the scrubber, the terms B and K_{pg} can be calculated and the collection efficiency (penetration) can be estimated using the appropriate figure [Figure 10-1(a), (b), or (c)].



(a) Geometric standard deviation σ_{gm} equals 2.5

(b) Geometric standard deviation σ_{gm} equals 5.0

(c) Geometric standard deviation σ_{gm} equals 7.5

Figure 10-1. Overall penetration, $\overline{\mathrm{Pt}}$, versus B with K_{pg} as a parameter, with different geometric standard deviations σ_{gm}

Source: Yung et al. 1977.

Example 10-1 illustrates how to use the infinite-throat model to predict the performance of a venturi scrubber. When using the equations given in the model, make sure that the units for each equation are consistent.

Example 10-1

Cheeps Disposal Inc. is planning to install a hazardous-waste incinerator that will burn both liquid and solid waste materials. The exhaust gas from the incinerator will pass through a quench spray and then into a venturi scrubber and finally through a packed bed scrubber. Caustic will be added to the scrubbing liquor to remove any HCl from the flue gas and to control the pH of the scrubbing liquor. The uncontrolled particulate emissions leaving the incinerator are estimated to be 1,100 kg/h (maximum average). The local air pollution regulation states that particulate emissions must not exceed 10 kg/h. Using the following data, estimate the particulate collection efficiency of the venturi scrubber.

d_{ps},	mass-median particle size (physical)	9.0 μm
σ_{gm},	geometric standard deviation	2.5
ρ_p,	particle density	1.9 g/cm^3
μ_g,	gas viscosity	2.0×10^{-4} g/cm•s
v_g,	gas kinematic viscosity	0.2 cm^2/s
ρ_g,	gas density	1.0 kg/m^3
Q_G,	gas flow rate	15 m^3/s
v_{gt},	gas velocity in venturi throat	9,000 cm/s
T_g,	gas temperature (in venturi)	80°C
T_l,	water temperature	30°C
ρ_l,	liquid density	1,000 kg/m^3
Q_L,	liquid flow rate	0.014 m^3/s
L/G,	liquid-to-gas ratio	0.0009 L/m^3

Solution

Figure 10-2 gives an overview of the solution presented here. As you can see from the diagram, you must solve many equations and make many calculations to obtain the collection efficiency of the scrubbing system. Equations in the early steps serve as inputs to the later ones.

Overview of steps for completing Example 10-1

Step 1

Calculate C_c, Cunningham slip correction factor

$$C_c = 1 + \frac{\left(6.21 \times 10^{-4}\right)T}{d_{ps}} \qquad (10\text{-}12)$$

Values are given for: T, d_{ps}

Step 2

Calculate d_{pg}, particle aerodynamic geometric mean diameter

$$d_{pg} = d_{ps}\left(C_c \times \rho_p\right)^{0.5} \qquad (10\text{-}11)$$

Values are given for: d_{ps}, ρ_p

Step 3

Calculate d_d, droplet diameter

$$d_d = \frac{50}{v_{gt}} + 91.8\,(L/G)^{1.5} \qquad (10\text{-}6)$$

Values are given for: v_{gt}, L/G

Step 4

Calculate K_{pg}, the inertial parameter for mass-median diameter

$$K_{pg} = \frac{d_{pg}^{\,2}\, v_{gt}}{9\mu_g\, d_d} \qquad (10\text{-}10)$$

Values are given for: v_{gt}, μ_g

Step 5

Calculate N_{Reo}, Reynolds Number

$$N_{Reo} = \frac{v_{gt}\, d_d}{\nu_g} \qquad (10\text{-}9)$$

Values are given for: v_{gt}, ν_g
Value for d_d is calculated in step 3

Step 6

Calculate C_D, drag coefficient for liquid at the throat entrance

$$C_D = 0.22 + \frac{24}{N_{Reo}}\left(1 + 0.15\, N_{Reo}^{0.6}\right) \qquad (10\text{-}8)$$

Step 7

Calculate B, parameter for L/G ratio

$$B = (L/G)\frac{\rho_l}{\rho_g C_D} \qquad (10\text{-}7)$$

Values are given for: L/G, ρ_l, ρ_g

Step 8

Calculate the overall penetration, $\overline{Pt}$ using Figure 10-1.

Values for K_{pg}, and B are calculated in steps 4 and 7

Step 9

Calculate collection efficiency

$$\eta = 1 - \overline{Pt}$$

Figure 10-2. Overview of steps for completing Example 10-1

1. **Calculate the Cunningham slip correction factor, C_c,** using Equation 10-12.

$$C_c = 1 + \frac{(6.21 \times 10^{-4})T}{d_{ps}}$$

Given: d_{ps} = 9.0 μm, the mass-median particle size (physical)
T_g = 80 °C, the gas temperature

$$C_c = 1 + \frac{(6.21 \times 10^{-4})(273 + 80)}{9\ \mu m}$$
$$= 1.024$$

2. **Calculate the particle aerodynamic geometric mean diameter, d_{pg},** using Equation 10-11.

$$d_{pg} = d_{ps}(C_c \times \rho_p)^{0.5}$$

Given: d_{ps} = 9.0 μm, mass-median particle size (physical)
ρ_p = 1.9 g/cm^3, particle density

From step 1: C_c = 1.024

$$\begin{aligned} d_{pg} &= 9\mu m\,(1.024 \times 1.9\ g/cm^3)^{0.5} \\ &= 12.6\ \mu mA \\ &= 12.6 \times 10^{-4}\ cmA \end{aligned}$$

Note: Steps 1 and 2 above would not have been required if the particle diameter had been given as the aerodynamic geometric mean diameter, d_{pg}, **and expressed in units of μmA.**

3. **Calculate the droplet diameter, d_d,** from Equation 10-6 (Nukiyama Tanasawa equation).

$$d_d = \frac{50}{v_{gt}} + 91.8\,(L/G)^{1.5}$$

Given: v_{gt} = 9,000 cm/s, gas velocity in venturi throat
L/G = 0.0009 L/m^3

$$d_d = \frac{50}{9{,}000\text{ cm/s}} + 91.8\,(0.0009)^{1.5}$$
$$= 0.0080\text{ cm}$$

4. **Calculate the inertial parameter for the mass-median diameter, K_{pg},** using Equation 10-10.

$$K_{pg} = \frac{{d_{pg}}^2 v_{gt}}{9\mu_g\, d_d}$$

Given: v_{gt} = 9,000 cm/s, gas velocity in venturi throat
μ_g = 2.0 × 10^{-4} g/cm•s, gas viscosity

From step 2: d_{pg} = 12.6 × 10^{-4} cmA
From step 3: d_d = 0.008 cm

$$K_{pg} = \frac{\left(12.6\times10^{-4}\text{ cmA}\right)^2\left(9{,}000\text{ cm/s}\right)}{9\left(2.0\times10^{-4}\text{ g/cm}\bullet\text{s}\right)\left(0.008\text{ cm}\right)}$$
$$= 992$$

5. **Calculate the Reynolds Number, N_{Reo},** using Equation 10-9.

$$N_{Re\,o} = \frac{v_{gt} d_d}{\nu_g}$$

Given: v_{gt} = 9,000 cm/s, gas velocity in venturi throat
ν_g = 0.2 cm^2/s, gas kinematic viscosity

From step 3: d_d = 0.008 cm

$$N_{Reo} = \frac{(9{,}000\text{ cm/s})(0.008\text{ cm})}{0.2\text{ cm}^2\text{/s}}$$
$$= 360$$

6. **Calculate the drag coefficient for the liquid at the throat entrance, C_D,** using Equation 10-8.

$$C_D = 0.22 + \frac{24}{N_{Re\,o}}\left(1 + 0.15\, N_{Re\,o}^{0.6}\right)$$

From step 5: N_{Reo} = 360

$$C_D = 0.22 + \frac{24}{360}\left(1 + 0.15(360)^{0.6}\right)$$

$$= 0.628$$

7. **Calculate the parameter characterizing the liquid-to-gas ratio, B,** using Equation 10-7.

$$B = (L/G)\frac{\rho_l}{\rho_g C_D}$$

Given: L/G = 0.0009 L/m^3

ρ_l = 1,000 kg/m^3

ρ_g = 1.0 kg/m^3

$$B = \left(0.0009\ \mathrm{L/m^3}\right)\frac{1{,}000\ \mathrm{kg/m^3}}{\left(1.0\ \mathrm{kg/m^3}\right)(0.628)}$$

$$= 1.43$$

8. **Determine the overall penetration, $\overline{Pt}$,** from Figure 10-3. The geometric standard deviation, σ_{gm} , is 2.5.

σ_{gm} = 2.5

From step 4: K_{pg} = 992, use the line for 1,000

From step 7: B = 1.43

In figure 10-3, read $\overline{Pt}$ = 0.008.

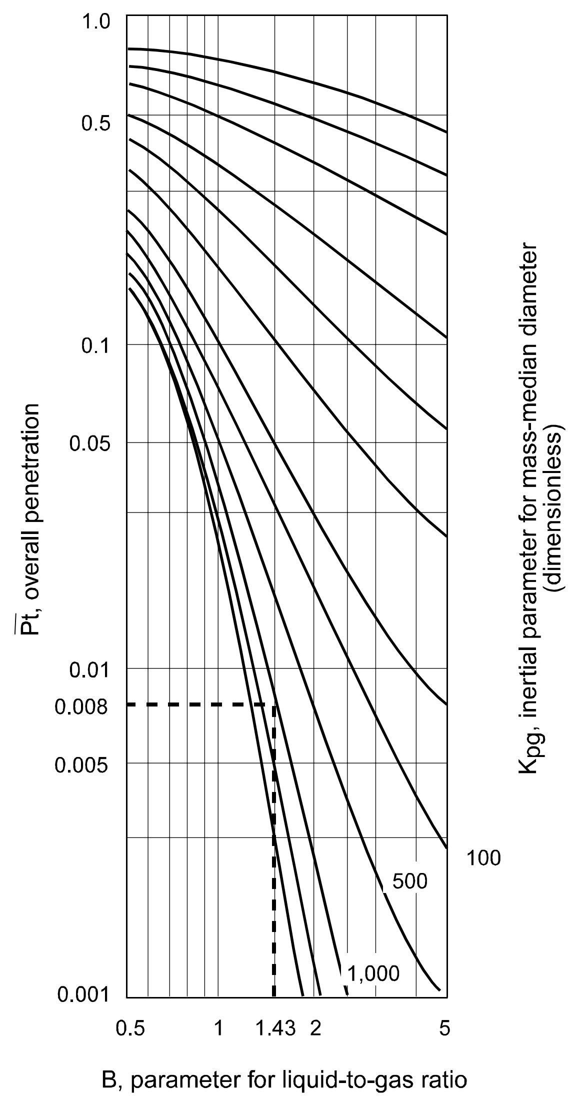


Figure 10-3. Overall penetration, $\overline{Pt}$, for Example 10-1, where the standard deviation, σ_{gm}, is equal to 2.5

9. **Calculate the collection efficiency** using equation below.

$$\eta = 1 - \overline{Pt}$$

From step 8: $\overline{Pt} = 0.008$

$$\begin{aligned} \eta &= 1 - 0.008 \\ &= 0.992 \\ &= 99.2\% \end{aligned}$$

10. **Determine whether the local regulations for particulate emissions are being met.** The local regulations state that the particulate emissions cannot exceed 10 kg/h. The required collection efficiency can be calculated by using the equation below.

$$\eta_{required} = \frac{dust_{in} - dust_{out}}{dust_{in}}$$

Given: $dust_{in}$ = 1,100 kg/h, the dust concentration leading into theventuri

$dust_{out}$ = 10 kg/h, the dust concentration leaving the venturi

$$\begin{aligned} \eta_{required} &= \frac{1100\,\text{kg/h} - 10\,\text{kg/h}}{1100\,\text{kg/h}} \\ &= 0.991 \\ &= 99.1\% \end{aligned}$$

Note: Figure 10-1 can also be used to determine some of the required operating variables. This can be done by solving the example problem in reverse. By entering the figures at the required efficiency (or $\overline{Pt}$), one can obtain various sets of K_{pg} and B values. These values for B and K_{pg} can be used to calculate the required L/G ratio or gas velocity in venturi throat (v_{gt}) for a specific collection efficiency.

To test your knowledge of the preceding section, answer the questions in Part 1 of the Review Exercise and work problem 1.

Contact Power Theory

A more general theory for estimating collection efficiency is the **contact power theory**. This theory is based on a series of experimental observations made by Lapple and Kamack (1955). The fundamental assumption of the theory is:

"When compared at the same power consumption, all scrubbers give substantially the same degree of collection of a given dispersed dust, regardless of the mechanism involved and regardless of whether the pressure drop is obtained by high gas flow rates or high water flow rates." (Lapple and Kamack 1955)

In other words, collection efficiency is a function of how much power the scrubber uses, and not of how the scrubber is designed. This has a number of implications in the evaluation and selection of wet collectors. Once you know the amount of power needed to attain a certain collection efficiency, the claims about specially located nozzles, baffles, etc. can be evaluated more objectively. The choice between two different scrubbers with the same power requirements may depend primarily on ease of maintenance.

Semrau (1959 and 1963) developed the contact power theory from the work of Lapple and Kamack (1955). The theory, as developed by Semrau, is empirical in approach and relates the **total pressure loss, P_T**, of the system to the collection efficiency.

The total pressure loss is expressed in terms of the power expended to inject the liquid into the scrubber plus the power needed to move the process gas through the system.

$$P_T = P_G + P_L \tag{10-13}$$

Where:
- P_T = total contacting power, kWh/1,000 m^3 (hp/1,000 acfm)
- P_G = power input from gas stream, kWh/1,000 m^3 (hp/1,000 acfm)
- P_L = power input from liquid injection, kWh/1,000 m^3 (hp/1,000 acfm)

Note: The total contacting power (or pressure loss), P_T, should not be confused with penetration, Pt, defined in the previous section. Penetration is the symbol used by Calvert to express the fraction of particulate matter escaping from a collector.

The **power expended in moving the gas** through the system, P_G, is expressed in terms of the scrubber pressure drop.

$$P_G = (2.724 \times 10^{-4})^* \Delta p, \text{ kWh/1,000 m}^3 \text{ (metric units)}$$

or (10-14)

$$P_G = 0.1575^* \Delta p, \text{ hp/1,000 acfm (English units)}$$

Where: Δp = pressure drop, kPa (in. H_2O)

*Note: These values are based on gas density at standard (70°F and 1 atm) conditions; see derivation of equation in Richards 1983.

The **power expended in the liquid stream**, P_L, is expressed as:

$$P_L = 0.28\ p_L(Q_L/Q_G), \text{ kWh/1,000 m}^3 \text{ (metric units)}$$

or (10-15)

$$P_L = 0.583\ p_L(Q_L/Q_G), \text{ hp/1,000 acfm (English units)}$$

Where: p_L = liquid inlet pressure, 100 kPa (lb/in.^{2})
Q_L = liquid feed rate, m^3/h (gal/min)
Q_G = gas flow rate, m^3/h (ft^3/min)

The constants given in the expressions for P_G and P_L incorporate conversion factors to put the terms on a consistent basis.

The total power can therefore be expressed as:

$$P_T = P_G + P_L$$

$$P_T = 2.724 \times 10^{-4} \Delta p + 0.28\ p_L(Q_L/Q_G), \text{ kWh/1,000 m}^3$$

or (10-16)

$$P_T = 0.1575 \Delta p + 0.583\ p_L(Q_L/Q_G), \text{ hp/1,000 acfm}$$

The problem now is to correlate this with scrubber efficiency.

Equation 10-2 in this lesson shows that efficiency is an exponential function of the system variables for most types of collectors.

$$\eta = 1 - e^{-f(\text{system})}$$

Semrau defines the function of the system variables, f (system), as:

$$f\,(\text{system}) = N_t = \alpha P_T^{\beta} \qquad (10\text{-}17)$$

Where: N_t = number of transfer units
P_T = total contacting power
α and β = empirical constants which are determined from experiment and depend on the characteristics of the particles

The number of transfer units (N_t) is a concept that originated with plate towers. Plate towers have discrete separation stages. A plate tower with three plates has three separation stages or transfer units. Transfer units apply as well to packed towers, even though they have continuous (rather than discrete) separations. The number of transfer units is higher in systems where the pollutants are difficult to capture. Transfer units will be discussed in greater detail in Lesson 11.

Combining Equations 10-2 and 10-17, efficiency then becomes:

$$\eta = 1 - e^{-\alpha P_T^{\beta}} \qquad (10\text{-}18)$$

Table 10-2 gives values of α and β for different industries. The values of α and β can be used in either the metric or English units.

Table 10-2. Parameters α and β for the contact power theory

Scrubber design	Aerosol	α	β
Venturi	Talc dust	2.97	0.362
	Phosphoric acid mist	1.33	0.647
	Foundry cupola dust	1.35	0.621
	Open-hearth steel furnace fume	1.26	0.569
	Odorous mist	0.363	1.41
Venturi evaporator	Hot black liquor gas	0.522	0.861
Venturi and cyclonic spray	Lime kiln dust (raw)	1.47	1.05
	Black liquor furnace fume	1.75	0.620
	Ferrosilicon furnace fume	0.870	0.459
	Lime kiln dust (prewashed)	0.915	1.05
	Black liquor fume	0.740	0.861

Continued on next page

Table 10-2. *(continued)* Parameters α and β for the contact power theory

Scrubber design	Aerosol	α	β
Venturi condensation scrubber with:			
1. Mechanical spray generation	Copper sulfate	0.390	1.14
2. Hydraulic nozzles	Copper sulfate	0.562	1.06
Orifice	Talc dust	2.70	0.362
Cyclone	Talc dust	1.16	0.655

Source: Semrau 1960.

The contact power theory cannot predict efficiency from a given particle-size distribution. The contact power theory gives a relationship which is independent of the size of the scrubber. With this observation, a small pilot scrubber could first be used to determine the pressure drop needed for the required collection efficiency. The full-scale scrubber design could then be scaled up from the pilot information.

Example 10-2

A wet scrubber has been proposed to control particulate emissions from a foundry cupola. Stack test results reveal that the particulate emissions must be reduced by 85% to meet emission standards. If a 100-acfm pilot unit is operated with a water flow rate of 0.5 gal/min at a water pressure of 80 psi, what pressure drop (Δp) would be needed across a 10,000-acfm scrubber unit?

Solution

1. **From Table 10-2, read the α and β parameters for foundry cupola dust.**

$$\alpha = 1.35$$
$$\beta = 0.621$$

2. **Calculate the number of transfer units, N_t,** substituting Equation 10-17 into Equation 10-2.

$$\eta = 1 - e^{-N_t}$$

$$N_t = \ln \frac{1}{1-\eta}$$

Given: η = 85%, collection efficiency

$$N_t = \ln\frac{1}{1-0.85}$$

$$= \ln 6.66$$

$$= 1.896$$

3. **Calculate the total contacting power, P_T,** using Equation 10-18.

$$N_t = \alpha P_T{}^{\beta}$$

From step 1: $\alpha = 1.35$
$\beta = 0.621$

From step 2: $N_t = 1.896$

$$1.896 = 1.35\ P_T{}^{0.621}$$

$$1.404 = P_T{}^{0.621}$$

$$\ln 1.404 = 0.621 \ln P_T$$

$$0.3393 = 0.621 \ln P_T$$

$$0.5464 = \ln P_T$$

$$P_T = 1.73 \text{ hp/1,000 acfm}$$

4. **Calculate the pressure drop, Δp,** using Equation 10-16.

$$P_T = 0.1575\ \Delta p + 0.583\ p_L\left(\frac{Q_L}{Q_G}\right)$$

Given:
P_L = 80 psi, liquid inlet pressure
Q_L = 0.5 gal/min, liquid feed rate
Q_G = 100 acfm, gas flow rate

From step 3: P_T = 1.73 hp/1,000 acfm

$$1.73 = 0.1575\ \Delta p + 0.583(80)\left(\frac{0.5}{100}\right)$$

$$\Delta p = 9.5 \text{ in. } H_2O$$

From the data in Table 10-2, you can see that the usefulness of Equation 10-18 is limited due to the lack of α and β values. Also, the contact power theory does not apply to a number of new wet collecting systems where a combination of collecting mechanisms are used, such as condensation scrubbers. The theory applies best when the power is applied in one scrubbing area (McIlvaine 1977), such as in a venturi scrubber. Multiple-stages devices and packed towers will have collection efficiencies varying from those of a venturi scrubber for a given power input. However, the concept of the contact power theory is still a very useful tool in evaluating scrubber design.

Pressure Drop

As discussed earlier, a number of factors affect particle capture in a scrubber. One of the most important for many scrubber types is pressure drop. Pressure drop is the difference in pressure between the inlet and the outlet of the scrubbing process. It is the sum of the energy required to accelerate and move the gas stream and the frictional losses as the gases move through the scrubbing system.

The following factors affect the pressure drop in a scrubber:

- Scrubber design and geometry
- Gas velocity
- Liquid-to-gas ratio

As with calculating collection efficiency, no one equation can predict the pressure drop for all scrubbing systems.

Many theoretical and empirical relationships are available for estimating the pressure drop across a scrubber. Generally, the most accurate are those developed by scrubber manufacturers for *their* particular scrubbing systems. Due to the lack of validated models, it is recommended that users consult the vendor's literature to estimate pressure drop for the particular scrubbing device of concern.

One expression was developed for venturis and is widely accepted. The correlation proposed by Calvert (Yung et al. 1977) is:

$$\Delta p = 8.24 \times 10^{-4}\,(v_{gt})^2\,(L/G) \qquad \text{(metric units)}$$

or (10-19)

$$\Delta p = 4.0 \times 10^{-5}\,(v_{gt})^2\,(L/G) \qquad \text{(English units)}$$

Where:
Δp = pressure drop, cm H_2O (in. H_2O)
v_{gt} = velocity of gas in the venturi throat, cm/s (ft/sec)
L/G = liquid-to-gas ratio, dimensionless, L/m^3 ($gal/1000\ ft^3$)

Using Equation 10-19 to calculate the pressure drop for the conditions given in Example 10-1, we get the following:

Given: v_{gt} = 9,000 cm/s
L/G = 0.0009 L/m^3

$$\Delta p = 8.24 \times 10^{-4} (9{,}000)^2 (0.0009)$$
$$= 60 \text{ cm } H_2O \text{ (or 24 in. } H_2O)$$

Using Pilot Methods to Design Scrubbers

The semi-empirical theories previously discussed are useful for scrubber design and evaluation exercises because they can give qualitatively correct information. However, they have a number of practical limitations. It is not common practice to choose scrubber systems based only on this information. The uncertainties involved in particle-size determinations and the questions associated with using empirically determined parameters restrict the use of theoretical methods. Basically, too many variables are involved and accounting for them all in a simple theory is too difficult. The time and expense needed to obtain good input data for these methods may be better spent in developing pilot plant information.

Scrubbers that work primarily through impaction mechanisms have certain performance characteristics (such as efficiency and pressure drop) which are independent of scale. This consequence of the contact power principle provides the basis for using pilot systems. By using a small-scale scrubber (100 to 1,000 cfm) on the exhaust gas stream, the effectiveness of the equipment for removing the actual particles in the gas can be experimentally determined.

Pilot systems ranging from 170 m^3/h (100 cfm) units to one-tenth the size of full-scale plants have been developed in the past. McIlvaine (1977) has compared the effectiveness of the various design methods. His work is summarized in Table 10-3.

Table 10-3. Methods for predicting venturi scrubber pressure requirements

Description		Expense (relative scale)	Time (months)
Most reliable	1/10 size full-scale plants	100-1,000	12-24
↓	2000-cfm pilot units	30	3-6
↓	100-cfm pilot units	5	2-3
↓	Empirical curves based on similar processes	0.2	0.2
↓	Impactor in situ particle sizing	2	1
Least reliable			

The design of a wet collector system for a particulate-emission problem requires more than the application of a few design equations. The experience of scrubber manufacturers with specific industry installations, coupled with the use of pilot units, provides more reliable ways to determine the size of a system for a wide range of operating conditions. In many cases, theoretical models can complement such studies and provide qualitative data for wet collector evaluations.

Summary

When reviewing design plans for a proposed new wet scrubbing system, the most useful information is operating data from an installation on similar sources. There are theoretical relationships that can be used to estimate scrubber performance; however, they are specific to the physical design of one scrubbing system and often all the needed inputs are not available. Therefore, an evaluation of wet scrubber design plans should involve utilizing both theoretical relationships and operating information from similar sources to assure that the proposed system design can achieve the desired control efficiency and addresses potential operating problems.

There are a number of parameters that affect particle removal efficiency and must be considered in the design of a wet scrubbing system; they are the following:

- Dust properties (particle size distribution being most important)
- Exhaust gas characteristics
- Static pressure drop
- Scrubber liquid flow rate
- Required particle removal efficiencies
- Removing entrained liquid droplets

The infinite throat model (for venturis only) and the contact power are two methods used to estimate scrubber performance that were discussed in this lesson. The infinite throat model correlates with operating data but is applicable only to venturi scrubbers. The contact power theory is applicable to various scrubber designs, but must have pilot plant data to predict efficiency.

To test your knowledge of the preceding section, answer the questions in Part 2 of the Review Exercise and work problems 2 and 3.

Review Exercise

Questions

Part 1

1. Which approach(es) can be used to evaluate the capabilities of scrubbing systems?
   a. Empirical relationships
   b. Theoretical models
   c. Pilot scale test data
   d. a and b, only
   e. a, b, and c
2. Two important parameters in the design and operation of wet scrubbing systems that are a function of the process being controlled are:
   a. Static pressure drop and collection efficiency
   b. L/G ratio and pressure drop
   c. Dust properties and exhaust gas characteristics
   d. Liquid flow rate and L/G ratio
3. True or False? Particle size distribution is the most critical parameter in choosing the most effective scrubber design and determining the overall collection efficiency.
4. Static pressure drop of a system is dependent on the:
   a. Mechanical design of the system
   b. Collection efficiency required
   c. Size of the system
   d. a and b, only
5. The scrubber used most often to remove particulate matter from exhaust streams is a ____________________ scrubber.
6. The term *penetration* is defined as:
   a. The fraction of particles collected in a scrubber
   b. The amount of gaseous pollutants absorbed in the scrubbing liquor
   c. The fraction of particles that passes through a scrubber uncollected
7. True or False? There is no one simple equation that can be used to estimate scrubber collection efficiency for all scrubber types.
8. True or False? Efficient particle removal requires low gas-to-liquid (relative) velocities.
9. A model used to estimate particle collection in venturi scrubbers is:
   a. The infinite-throat model
   b. The penetration model
   c. The short-stack model
   d. The impaction model

Part 2

10. The contact power theory is dependent on ____________________ data to determine required collection efficiency:

    a. Process
    b. Pilot test
    c. Theoretical
    d. Fan curve

11. In the equation used in the contact power theory, $P_T = P_G + P_L$, the symbol P_T represents:

    a. The penetration of the system
    b. The collection efficiency
    c. The total pressure loss, or contacting power, of the scrubbing system

12. According to the contact power theory, the ____________________ the pressure drop is across the scrubbing system, the higher the collection efficiency will be.

    a. Lower
    b. Higher

13. Which of the following factors affect the pressure drop of a scrubbing system?

    a. Scrubber design and geometry
    b. Gas velocity
    c. Liquid-to-gas ratio
    d. All of the above

Problem 1

A company has submitted an application to increase production of its lime kiln by 20%. The kiln is currently controlled by a venturi scrubber that the applicant feels is capable of handling the added gas volume and dust loading. The system has a quench chamber that is capable of cooling the extra gas volume. Given the information below, calculate the new collection efficiency.

		Existing	**Proposed**
d_{ps} ,	mass-median particle size (physical)	8.0 μm	8.0 μm
σ_{gm},	geometric standard deviation of particle distribution	2.5	2.5
ρ_p,	particle density	1.7 g/cm^3	1.7 g/cm^3
μ_g,	gas viscosity	2.0×10^{-4} g/cm·s	2.0×10^{-4} g/cm·s
ν_g,	gas kinematic viscosity	0.2 cm^2/s	0.2 cm^2/s
ρ_g,	gas density	1.0 kg/m^3	1.0 kg/m^3
Q_G,	gas flow rate	18 m^3/s	22.5 m^3/s
v_{gt},	gas velocity in venturi throat	85,000 cm/s	10,625 cm/s
T_g,	gas temperature (in venturi)	80^{o}C	80^{o}C
T_l,	water temperature	30^{o}C	30^{o}C
ρ_l,	liquid density	1,000 kg/m^3	1,000 kg/m^3
Q_L,	liquid flow rate	0.016 L/s	0.016 L/s
L/G,	liquid-to-gas ratio	0.00089	0.00071
	dust loading	455 kg/hr	545 kg/hr
	efficiency	98.8%	calculate

Problem 1: Student Worksheet

(This space is provided for you to work problem 1)

Problem 1: Student Worksheet (cont'd)

(This space is provided for you to work problem 1)

Problem 1: Student Worksheet (cont'd)

(This space is provided for you to work problem 1)

Problem 1: Student Worksheet (cont'd)

(This space is provided for you to work problem 1)

Problem 2

A wet scrubber is used to control dust emissions from a foundry. The system design and test data is summarized below. Due to new air quality requirements, the source will be required to control particulate to a removal efficiency of 95%. What would be the new pressure drop to attain 95% removal if no other operational changes were made?

Operating test data

Δp,	pressure drop	9.0 in. of H_2O
Q_L,	liquid feed rate	150 gal/min
Q_G,	gas flow rate	22,000 acfm
p_L,	water pressure	90 psi

Problem 2: Student Worksheet

(This space is provided for you to work problem 2)

Problem 2: Student Worksheet (cont'd)

(This space is provided for you to work problem 2)

Problem 3

A company proposes to increase the production rate of its lime kiln by 20%. Calculate the increase in pressure drop that will result from the new operating conditions.

		Existing	Proposed
v_{gt},	gas velocity at the throat	8,500 cm/s	10,625 cm/s
L/G	(dimensionless in metric units)	0.00089	0.00071

Problem 3: Student Worksheet

(This space is provided for you to work problem 3)

Problem 3: Student Worksheet

(This space is provided for you to work problem 3)

Review Exercise Answers

Answers to Questions

Part 1

1. **e. a, b, and c**
   The following approaches can be used to evaluate the capabilities of scrubbing systems:
   - Empirical relationships
   - Theoretical models
   - Pilot scale test data
2. **c. Dust properties and exhaust gas characteristics**
   Two important parameters in the design and operation of wet scrubbing systems that are a function of the process being controlled are dust properties and exhaust gas characteristics.
3. **True**
   Particle size distribution is the most critical parameter in choosing the most effective scrubber design and determining the overall collection efficiency.
4. **d. a and b, only**
   Static pressure drop of a system is dependent on the:
   - Mechanical design of the system
   - Collection efficiency required
5. **Venturi**
   The scrubber used most often to remove particulate matter from exhaust streams is a venturi scrubber.
6. **c. The fraction of particles that passes through a scrubber uncollected**
   The term *penetration* is defined as the fraction of particles that passes through a scrubber uncollected.
7. **True**
   There is no one simple equation that can be used to estimate scrubber collection efficiency for all scrubber types.
8. **False**
   Efficient particle removal requires high gas-to-liquid (relative) velocities.
9. **a. The infinite-throat model**
   The infinite-throat model is used to estimate particle collection in venturi scrubbers.

Part 2

10. **b. Pilot test**
    The contact power theory is dependent on pilot test data to determine required collection efficiency.

11. **c. The total pressure loss, or contacting power, of the scrubbing system**
In the equation used in the contact power theory, $P_T = P_G + P_L$, the symbol P_T represents the total pressure loss, or contacting power, of the scrubbing system.

12. **b. Higher**
According to the contact power theory, the higher the pressure drop is across the scrubbing system, the higher the collection efficiency will be.

13. **d. All of the above**
The following factors affect the pressure drop of a scrubbing system:
    - Scrubber design and geometry
    - Gas velocity
    - Liquid-to-gas ratio

Solution to Problem 1

Answer: The collection efficiency of the venturi scrubber under the new scenario is **97.5%.**

Solution:

1. **Calculate the particle aerodynamic geometric mean diameter, d_{pg}.** Since the mass-median particle size, d_{ps}, is given, first calculate the Cunningham slip correction factor, C_c, using Equation 10-12.

$$C_c = 1 + \frac{(6.21 \times 10^{-4})T}{d_{ps}}$$

Given: d_{ps} = 8.0 μm, mass-median particle size (physical)
T = 80°C, gas temperature

$$C_c = 1 + \frac{(6.21 \times 10^{-4})\,(273 + 80)}{8}$$

$$= 1.027$$

Now, calculate d_{pg} using Equation 10-11.

$$d_{pg} = d_{ps}\,(C_c \times \rho_p)^{0.5}$$

Given: ρ_p = 1.7g/cm^3, particle density

$$\begin{aligned} d_{pg} &= 8.0\ \mu\text{m}\ (1.027 \times 1.7\ \text{g/cm}^3)^{0.5} \\ &= 10.57\ \mu\text{mA} \\ &= 10.57 \times 10^{-4}\ \text{cmA} \end{aligned}$$

2. **Calculate the droplet diameter, d_d,** from Equation 10-6 (Nukiyama Tanasawa equation).

$$d_d = 50/v_{gt} + 91.8\,(L/G)^{1.5}$$

Given: v_{gt} = 10,625 cm/s, gas velocity in venturi throat
L/G = 0.00071

$$d_d = \frac{50}{10{,}625\ \text{cm/s}} + 91.8\,(0.00071)^{1.5}$$

$$= 0.00644\ \text{cm}$$

3. **Calculate the inertial parameter for the mass-median diameter, K_{pg}**, using Equation 10-10.

$$K_{pg} = \frac{{d_{pg}}^2 v_{gt}}{9\mu_g d_d}$$

Given: v_{gt} = 10,625 cm/s, gas velocity in venturi throat
μ_g = 2.0×10^{-4} g/cm•s, gas viscosity

From step 1: d_{pg} = 10.57×10^{-4} cmA
From step 2: d_d = 0.00644 cm

$$K_{pg} = \frac{10.57 \times 10^{-4}\ \text{cmA})^2\ (10{,}625\ \text{cm/s})}{9\ (2.0 \times 10^{-4}\ \text{g/cm} \bullet \text{s})\ (0.00644\ \text{cm})}$$

$$=1{,}024$$

4. **Calculate the Reynolds Number, N_{Reo}**, using Equation 10-9.

$$N_{Reo} = \frac{v_{gt} d_d}{\nu_g}$$

Given: v_{gt} = 10,625 cm/s, gas velocity in venturi throat
ν_g = 0.2 cm^2/s, gas kinematic viscisity

From step 2: d_d = 0.00644 cm

$$N_{Reo} = \frac{(10{,}625\ \text{cm/s})(0.00644\ \text{cm})}{0.2\ \text{cm}^2/\text{s}}$$

$$= 342$$

5. **Calculate the drag coefficient for the liquid at the throat entrance, C_D**, using Equation 10-8.

$$C_D = 0.22 + \frac{24}{N_{Re\,o}}\left(1 + 0.15\,N_{Reo}^{0.6}\right)$$

From step 4: N_{Reo} = 342

$$C_D = 0.22 + \frac{24}{N_{Re\,o}}\left(1 + 0.15\,(342)^{0.6}\right)$$

$$= 0.639$$

6. **Calculate the parameter characterizing the liquid-to-gas, B**, using Equation 10-7.

$$B = (L/G)\frac{\rho_l}{\rho_g C_D}$$

Given:	L/G	=	0.00071
	ρ_l	=	1,000 kg/m^3, liquid density
	ρ_g	=	1.0 kg/m^3, gas density

From step 5: C_D = 0.639

$$B = (0.00071)\frac{1{,}000\ \text{kg}/\text{m}^3}{\left(1.0\ \text{kg}/\text{m}^3\right)(0.639)}$$

$$= 1.11$$

7. **Find the overall penetration, $\overline{Pt}$,** using Figure 10-1(a). The geometric standard deviation, σ_{gm}, is 2.5.

From step 3: K_{pg} = 1,024
From step 6: B = 1.11

Read $\overline{Pt}$ = 0.025 (Note: you have to estimate where the 1,024 line would be.)

8. **Calculate the collection efficiency** using the equation below.

$$\eta = 1 - \overline{Pt}$$

From step 7: $\overline{Pt} = 0.025$

$$\begin{aligned} \eta &= 1.0 - 0.025 \\ &= 0.975 \\ &= 97.5\% \end{aligned}$$

Solution to Problem 2

Answer: The new pressure drop to attain 95% particle removal is **21 in. of water**.

Solution:

1. **Obtain values for α and β for foundry cupola dust** from Table 10-2.

$$\alpha = 1.35$$

$$\beta = 0.621$$

2. **Calculate the number of transfer units, N_t,** using Equation 10-18.

$$\eta = 1 - e^{-N_t}$$

$$N_t = \ln \frac{1}{1-\eta}$$

Given: η = 95%, collection efficiency

$$N_t = \ln \frac{1}{1-0.95}$$

$$= \ln 20$$

$$= 3.0 \text{ transfer units}$$

3. **Calculate the total contacting power (P_T) required.**

$$N_t = \alpha P_T^{\beta}$$

From step 1: α = 1.35
β = 0.621

From step 2: N_t = 3.0

$$3.0 = 1.35 P_T^{0.621}$$

$$P_T^{0.621} = 3.0/1.35$$

$$P_T^{0.621} = 2.22$$

$$0.621 \ln P_T = \ln 2.22$$

$$\ln P_T = 1.28$$

$$P_T = 3.61 \text{ hp/1,000 acfm}$$

4. **Calculate the pressure drop** for the given operating conditions using Equation 10-16.

$$P_T = 0.1575\Delta p + 0.583\, p_L(Q_L/Q_G), \text{ hp/1,000 acfm}$$

Given:
p_L = 90 psi, water pressure
Q_L = 150 gal/min, liquid feed rate
Q_G = 22,000 acfm, gas flow rate

From step 3: P_T = 3.61 hp/1,000 acfm

$$3.61 = 0.1575\,\Delta p + 0.583\,(90)\,(150/22{,}000)$$

$$3.61 = 0.1575\,\Delta p + 0.358$$

$$\Delta p = 21 \text{ in. of water}$$

Solution to Problem 3

Answer: At the new operating conditions, the pressure drop will increase **13 cm (5 in.) of water.**

Solution:

1. **Solve for the existing pressure drop** using Equation 10-19.

$$\Delta p = 8.24 \times 10^{-4} (v_{gt})^2 (L/G) \qquad \text{(for metric units)}$$

Given: v_{gt} = 8,500 cm/s, existing gas velocity at throat
L/G = 0.00089, existing liquid-to-gas ratio

$$\Delta p = 8.24 \times 10^{-4} (8{,}500)^2 (0.00089)$$
$$\Delta p = 53 \text{ cm (or 21 in.) of water}$$

2. **Solve for new pressure drop** using Equation 10-19.

$$\Delta p = 8.24 \times 10^{-4} (v_{gt})^2 (L/G)$$

Given: v_{gt} = 10,625 cm/s, proposed gas velocity at throat
L/G = 0.00071, proposed liquid-to-gas ratio

$$\Delta p = 8.24 \times 10^{-4} (10{,}625)^2 (0.00071)$$
$$\Delta p = 66 \text{ cm (or 26 in.) of water}$$

3. **Solve for the increase in pressure drop at the new operating conditions**.

new Δp – old Δp	=	increase in Δp
In metric units: 66 cm – 53 cm	=	13 cm of water
In English units: 26 in. – 21 in.	=	5 in. of water

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